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MULTIWAVELENGTH PYROMETRY FOR NONGRAY SURFACES IN THE PRESENCE OF INTERFERING RADIATION

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SUMMARY

A NASA-developed multiwavelength pyrometry technique for nongray surfaces has been extended to also measure surface temperature in the presence of interfering radiation. This radiation is produced by heat lamps used to raise the temperature of the surface. The necessary instruments are a spectral radiometer, an auxiliary radiation source, and a computer. Four radiation spectra are recorded: (1) the unobstructed spectrum characterizing an auxiliary radiation source, (2) the unobstructed spectrum characterizing the interfering radiation, (3) the radiation spectrum consisting of surface emission plus the interfering radiation, and (4) a spectrum consisting of the radiations of (3) plus the reflected radiation due to the incidence of the auxiliary radiation source on this surface. With these spectra, application of two-variable, nonlinear, least-squares, curve-fitting computer software determines the surface temperature and the spectral emissivity. Use of the method to measure the surface temperature of silicon carbide under a simulated interference condition is demonstrated at a low temperature just above ambient. The instrumentation necessary to extend the method to elevated temperatures is discussed.

INTRODUCTION

Pyrometry is a favorite noncontact surface-temperature measurement method. Traditional pyrometers are the one- and two-color method. Multiwavelength pyrometers have recently been introduced to measure surface temperature (ref. 1).

Ceramic materials are to be used in the development of the next generation of propulsion systems. Accurate surface temperature measurement using noncontact methods is urgently needed in the development of these materials. Most ceramics materials are nongray, and their emissivity is known to be wavelength and even temperature dependent. Emissivity is low at short wavelengths, increases to almost unity at wavelengths around 8 or 10 μm , and then varies further at longer wavelengths (ref. 2). Therefore, traditional pyrometers are inherently inaccurate when applied measure ceramic surface temperatures, and unavoidable errors result (ref. 3). Furthermore, in the testing and development of these materials, intense external heat lamps are used as a heat source to raise the temperature of ceramic samples. The aforementioned pyrometers cannot discriminate between the reflected radiations originating from the heat lamps and radiations emitted from the measured surface.

Although we previously applied multiwavelength pyrometry to determine the surface temperature of gray surfaces in the presence of interfering radiation (refs. 4 and 5), that method also resulted in unavoidable error when applied to these nongray emissivity materials.

Multiwavelength pyrometry was developed at NASA Lewis to measure the temperature of a nongray silicon carbide ceramic surface by simultaneously measuring the surface emissivity

(refs. 6 and 7). The temperature measurement was accomplished with the acquisition and analysis of three radiation spectra from a nongray silicon carbide (SiC) surface. This multiwavelength pyrometry technique was thus extended to measure the temperature of a nongray surface in the presence of interfering radiation.

EXPERIMENTAL METHOD

Recall that the basic components of this pyrometer are a spectral radiometer, an auxiliary radiation source which can be turned on and off (either manually or by mechanical chopping), and a computer for data acquisition, data processing and numerical calculation (refs. 6 and 7). The SiC surface from which measurements were made was heated by allowing it to equilibrate in front of a blackbody furnace. The SiC sample completely covered the blackbody cavity opening. The blackbody furnace temperature was regulated by a temperature controller with $\pm 0.5^\circ\text{C}$ long-term stability. The auxiliary radiation source was regulated by a constant-current power supply such that its typical light output rms ripple was 0.05 percent.

In addition to the three spectra required for the nongray multiwavelength pyrometry (ref. 6), an additional spectrum was also needed to characterize the radiation of the interfering radiation source. It was acquired by allowing the unobstructed radiation from the interfering source to enter directly into the spectral radiometer. The four required spectra were

- (1) $S_0(\lambda)$: the spectrum of the auxiliary radiation source, which was acquired prior to real time measurement
- (2) $S_I(\lambda)$: the spectrum characterizing the spectral intensity of the extraneous interference radiation source
- (3) $S_{II}(\lambda)$: the spectrum of surface-emitted radiation $S_{II}^1(\lambda)$ plus interfering radiation $S_{II}^2(\lambda)$ reflected from the extraneous source
- (4) $S_{III}(\lambda)$: the radiation spectrum S_{II} plus the reflected radiation S_{IV} due to the incidence of the auxiliary radiation source on the surface

Note that some of the definitions of the spectra S_0 , S_I , S_{II} and S_{III} are different from those designated by the same symbols in reference 6.

The auxiliary radiation source was a 20-W infrared lamp. Spectrum $S_0(\lambda)$ was obtained from the geometry shown in figure 1. $S_0(\lambda)$ needed to be measured only once for such a radiation source.

Spectrum $S_I(\lambda)$ represented the spectral distribution of the interfering radiation. If this interference source were blackbody in origin, it would be represented analytically by a Planck function corresponding to its temperature. However, if it were more complicated in origin, its actual spectral distribution would be determined experimentally by using the geometry shown in figure 1.

Spectrum $S_{II}(\lambda)$ was obtained from a typical pyrometry measurement of a surface in the geometry shown in figure 2, with the auxiliary radiation source turned off. The emission spectrum $S_{II}^1(\lambda)$ of the nongray surface is described by a Planck function of temperature T modified by the wavelength-dependent emissivity (ref. 6) plus the interference radiation $S_{II}^2(\lambda)$ reflected by the measured surface.

Spectrum $S_{III}(\lambda)$ was also obtained from the same geometry shown in figure 2 but with the auxiliary radiation source turned on. Thus, $S_{III}(\lambda)$ was $S_{II}(\lambda)$ plus reflected radiation S_{IV} due to the auxiliary radiation source. Subtraction of spectrum $S_{II}(\lambda)$ from $S_{III}(\lambda)$ produced the reflected spectrum $S_{IV}(\lambda) = S_{III}(\lambda) - S_{II}(\lambda)$ due to the incidence of the auxiliary radiation source on the measured surface.

By application of the arguments advanced previously (ref. 6), the measured reflectivity $z(\lambda)$ at any wavelength was a ratio given by

$$z(\lambda) = \frac{S_{IV}(\lambda)}{S_0(\lambda)} = \frac{S_{III}(\lambda) - S_{II}(\lambda)}{S_0(\lambda)} \quad (1)$$

Because $S_0(\lambda)$ was measured on a direct path in figure 1 and $S_{IV}(\lambda)$ was measured on the reflected path in figure 2, the ratio $z(\lambda)$ included a constant factor f resulting from different conditions along the two paths. Two such conditions were the geometry of the optical beams and the nonspecular reflectivity surface. Thus, the true reflectivity r is

$$r(\lambda) = \frac{z(\lambda)}{f} \quad (2)$$

where f must be determined.

From reference 6, the emissivity e and reflectivity r of a surface are $e(\lambda, \beta, \theta, T_e)$ and $r(\lambda, \beta, \theta, T_e)$, where β and θ are the polar angular coordinate angles specifying a direction with reference to a suitably chosen coordinate system and T_e is the temperature of the reflecting surface. Even though the emissivity and reflectivity of a surface contain spectral, angular, and temperature dependence, only the spectral dependence remains important in pyrometry application (ref. 6). Therefore, by application of Kirchhoff's law, the emissivity of the surface is given simply by

$$\begin{aligned} e(\lambda) &= 1 - r(\lambda) \\ &= 1 - \frac{z(\lambda)}{f} \end{aligned} \quad (3)$$

In principle, the constant f can be determined from the geometry of the experimental setup. However, it is more conveniently determined by curve fitting.

The mathematical expression for the spectrum $S_{II}(\lambda)$ is written as a sum of two terms:

$$S_{II}(\lambda) = S_{II}^1(\lambda) + S_{II}^2(\lambda) \quad (4)$$

$S_{II}^1(\lambda)$ describes the surface emission radiation. It is a Planck function modified by the wavelength-dependent emissivity and is shown to be (assuming the direction of S_0 is not important or the same as S_I)

$$S_{II}^1(\lambda) = \left[1 - \frac{z(\lambda)}{f} \right] \frac{c_1}{\lambda^5} \frac{1}{\exp\left(\frac{c_2}{\lambda T}\right) - 1} \quad (5)$$

where c_1 and c_2 are the first and second radiation constants, and f and T are unknown parameters (ref. 6).

$S_{II}^2(\lambda)$ describes the reflected interfering radiation from the extraneous source $S_I(\lambda)$. It is proportional to the product of $r(\lambda)$, $S_I(\lambda)$, and a constant of proportionality g (due to beam geometry but different from f)

$$S_{II}^2(\lambda) = g r(\lambda) S_I(\lambda)$$

Substituting equation (2) gives

$$S_{II}^2(\lambda) = g z(\lambda) \frac{S_I(\lambda)}{f}$$

If the ratio g/f is replaced by

$$h = \frac{g}{f} \quad (6)$$

$$S_{II}^2(\lambda) = h z(\lambda) S_I(\lambda) \quad (7)$$

The quantity $z(\lambda)$ is obtained by using the wavelength-by-wavelength spectrum subtraction and division in equation (1). The adjustable parameters f , h (or g), and T are determined by applying-least squares curve fitting, with λ and $z(\lambda)$ treated as independent variables to fit the spectrum $S_{II}(\lambda)$ according to equations (4) to (7).

The unobstructed spectrum S_0 is shown in figure 3. It is the direct output of the detector in volts. As described in reference 6, it can be easily converted into energy units using the response function of the detector.

The interference source is simulated by a 40-W, nominal-temperature 644 K soldering iron which has a temperature controller of unknown temporal stability. It is placed in front of the SiC surface in approximately the same angular relationship as the auxiliary radiation source and is well shielded from the direct view of the spectral radiometer.

The spectrum S_I of the radiation emitted by the interference source (in arbitrary energy units) is shown in figure 4. The other spectra necessary for temperature measurement are acquired using the geometry shown in figure 2. The surface whose temperature was to be measured is a silicon carbide (SiC) wafer used previously (ref. 6).

RESULTS

The radiation spectra collected are shown in figure 5. $S_{II}^1(\lambda)$ is the surface emission spectrum at the test temperature. $S_{II}(\lambda)$ is the emission spectrum obtained in the presence of the interfering source with the auxiliary radiation source turned off, and $S_{III}(\lambda)$ is the spectrum obtained with the radiation source turned on. From observation of $S_{II}(\lambda)$, the contribution of the interference radiation to the pyrometer signal is clearly evident. At the short wavelengths, the interference component of the signal is over 50 percent. The total energy in S_{II} obtained by integrating the spectrum from 2.5 to 14.5 μm is 1.13 times that due to surface emission obtained by a similar integration. If this contribution is not accounted for, the temperature determined will be in error.

The spectra corresponding to S_{II} and S_{III} in figure 5 are reproduced in volts in figure 6. The difference between these two curves is the reflection spectrum S_{IV} due to the incidence of the auxiliary radiation source S_0 on the SiC surface (shown in fig. 7). Division of the spectrum of figure 7 by the unobstructed spectrum S_0 of figure 3 gives the quantity $z(\lambda)$ defined by equation (1); the result is shown in figure 8.

Commercially available nonlinear least-squares curve-fitting software was used to fit the spectrum S_{II} in figure 5 to the mathematical expression of equation (4) with equations (5) to (7) explicitly substituted. Curve fitting yielded a surface temperature of 341.3 K. The values of f and h are 0.375 and 3.49, respectively. The fitted curve, the sum of the two terms in equation (4), is shown in figure 9 together with the measured surface emission spectrum. Also shown is the 341.3 K Planck curve.

DISCUSSION

To demonstrate the importance of correcting for the reflective radiation from an extraneous source, spectrum S_I was omitted from consideration and only spectra S_0 , S_{II} , and S_{III} were subjected to the multiwavelength pyrometry analysis in which interference was not considered (ref. 6). The temperature was determined to be 373.4 K. The 341.3 K temperature measured by the current multiwavelength pyrometer included correction for interference radiation but was not simultaneously verified by another method during the experiment. However, from the good agreement between the fitted curve and the experimental spectrum shown in figure 9, we assert that this is the correct temperature. It was therefore concluded that neglecting the effect of interference would introduce an error of about 10 percent. A 0.125-mm (5-mil) chromel-alumel thermocouple was subsequently attached to the sample to permit as much contact as possible between its junction and the silicon carbide surface. The surface was then allowed to equilibrate to a temperature under the same condition (including the presence of a simulated extraneous radiation source) as before. The thermocouple measured a temperature of 339.7 K, which is in agreement with the multiwavelength pyrometry measurement to within 1 percent. This result confirms the assertion that a good fit to the radiation spectrum is an indication of accurate temperature measurement.

At higher temperatures, the surface emission will greatly overwhelm the radiation from the 20-W auxiliary radiation source. The reflected spectrum S_{IV} cannot be measurable by the subtraction of the two spectra obtained with and without the auxiliary source. However, the difference in signal can still be readily measured by chopping the auxiliary radiation source and using phase-sensitive detection schemes. Most spectral radiometers have an external signal

chopping capability. In this way, the subtraction of the two spectra, spectrum S_{II} from spectrum S_{III} , is automatically integrated into the signal processing and data acquisition as a single operation. The reflected spectrum S_{IV} is immediately obtained. After division by the direct spectrum S_0 , straight forward application of two-variable, least-squares, curve-fitting computer software will determine the temperature of the nongray surface with the effect of interference automatically taken into account.

CONCLUSION

The multiwavelength pyrometry for nongray surfaces determined the temperature of a silicon carbide surface in the presence of simulated interference radiation. Four radiation spectra were acquired and analyzed. The temperature was determined by application of two-variable, nonlinear, least-squares, curve-fitting software to fit the surface emission spectrum containing the interference radiation to a mathematical expression involving the wavelength-dependent emissivity of the surface and the interfering radiation source spectrum. The good agreement between an experimental spectrum and its fitted spectrum is an indication of the accurate temperature measurement that can be obtained by multiwavelength pyrometry.

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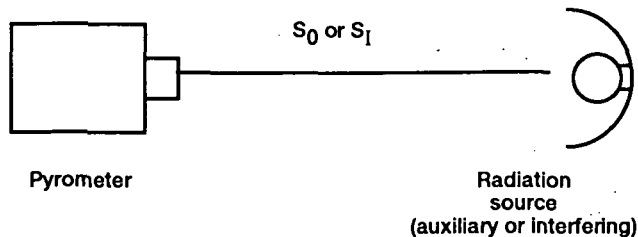


Figure 1.—Experimental arrangement to determine the unobstructed spectrum S_0 of the auxiliary radiation source or the interference spectrum S_I .

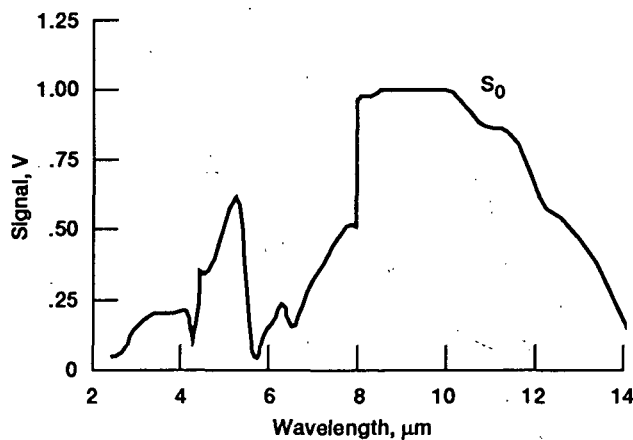


Figure 3.—The unobstructed spectrum S_0 (in volts) of the auxiliary radiation source.

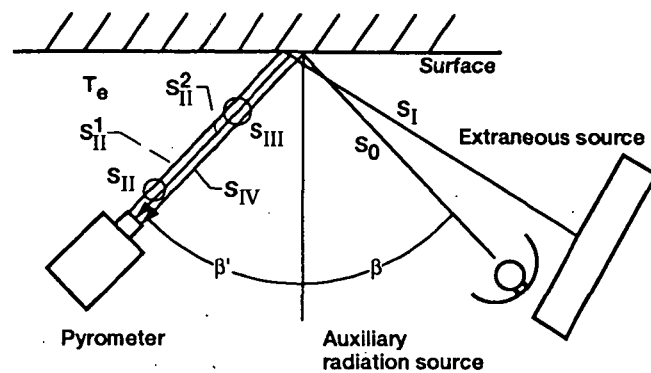


Figure 2.—Experimental arrangement of pyrometry components.

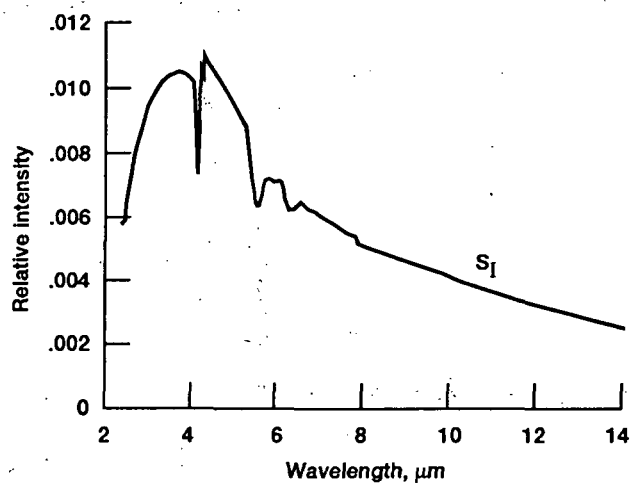


Figure 4.—Spectrum S_I (in arbitrary energy units) of the simulated interference source.

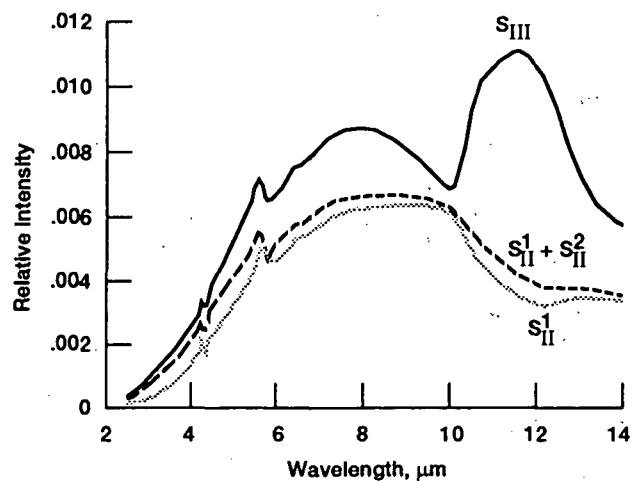


Figure 5.—Spectrum of silicon carbide; S_{II}^1 , surface emission; S_{II}^2 , surface emission plus interference (no auxiliary radiation); S_{III} , surface emission plus interference (with auxiliary radiation).

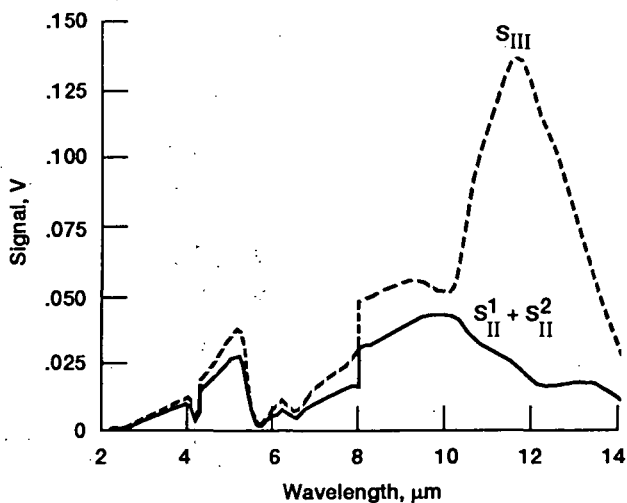


Figure 6.—Surface emission spectra (in volts) of silicon carbide surface; $S_{II}(\lambda) = S_{II}^1(\lambda) + S_{II}^2(\lambda)$ (auxiliary source off); S_{III} (auxiliary source on).

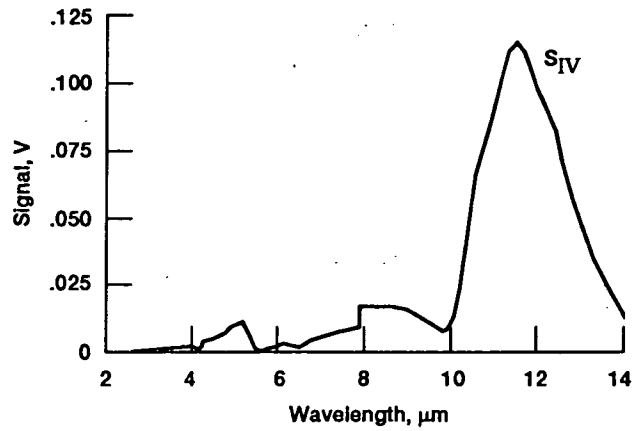


Figure 7.—Reflected spectrum S_{IV} (in volts) from a silicon carbide surface obtained by subtracting S_{II} from S_{III} .

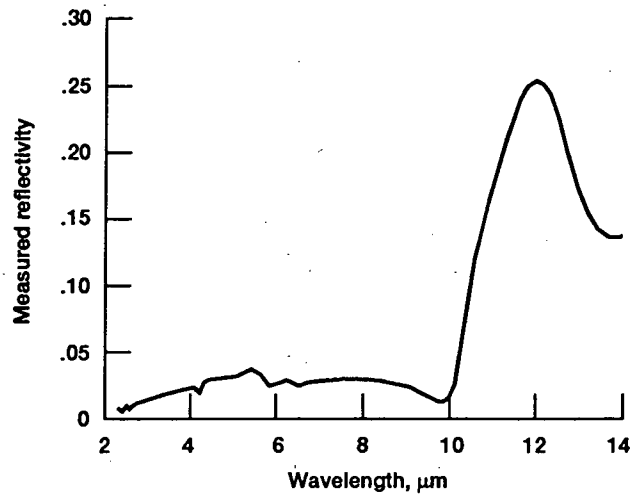


Figure 8.—Measured reflectivity $z(\lambda)$ of a silicon carbide surface obtained by dividing S_{IV} by S_0 .

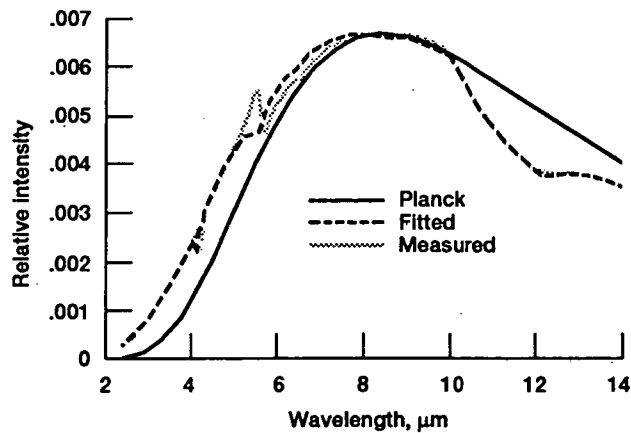


Figure 9.—Curves for spectrum S_{II} , spectrum according to equations (4) through (6), and Planck curve. Temperature, 341.3 K.

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